Chapter

Introductory Chapter: Earth Crust - Origin, Structure, Composition and Evolution

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1. Introduction

Earth crust is the thinnest and the most rudimentary layer that makes up the Earth, and yet, everything that has ever lived on Earth has called it home. The crust is a dynamic structure and it is one of the layers that make up our pale blue dot. The crust is referred to as a chemical layer that has varying chemical compositions. Two main types of crust are the oceanic crust and the continental crust, and they are different from each other. The differences are due to plate tectonics which then refers to plates and the movement of the plates above the asthenosphere, driving lithospheric processes that result in the formation and production of natural phenomena such as earthquakes and ridges. The crust is one of the five chemical layers of the Earth and is differentiated to show the distinct chemical properties occurring at each layer. The Earth's crust, along with the upper mantle, has its necessary role in the dynamic creation and destruction of the crustal surface in which all living organisms thrive on. This chapter will look at various aspects of the crust, and it will discuss the origin, structure and composition of the crust before elucidating its continued evolution to this day.

2. Origin

The early terrestrial crust appeared approximately 4.5 billion years ago, after the late stages of planetary accretion. This section describes the theories of the formation of the crust and discusses the origin of the oceanic and continental crust.

2.1 Theories about the formation of the crust

There are three main theories on the formation of the Earth's crust [1]: (1) inhomogeneous or heterogeneous accretion of the Earth model, (2) impact model and (3) terrestrial model.

The inhomogeneous model or the so-called the accretion model explains that the Earth's crust was formed during the accretion of the planet, with lighter and volatile elements forming a thin layer on the primitive planet which became the crust. This model suggests that non-volatile elements can only be found in the mantle; however, this is not true. Nonvolatile elements such as uranium and thorium are found on the Earth's crust [2], making this theory highly unlikely.

The impact model suggests that asteroids and other objects that impacted Earth melted and formed the crust [1]. The oceanic crust, which is mainly composed of basalt, could have been formed by a basalt asteroid that impacted the Earth. However, from the observations of the moon, basalts found in lunar maria were not due to an asteroid collision. Furthermore, the number of basalts produced from an impact event was too insignificant to form crusts [1]. In addition, a majority of the impact events on Earth happened after oceanic crusts were formed. Therefore, this theory is also unlikely as well.

The terrestrial model is the most likely explanation on the formation of the Earth's crust. This model explains that the crustal origin of the Earth was due to its internal processes. After the late accretion of the Earth, heat retained by the Earth resulted in the complete melting of the upper mantle, which formed a magma ocean that covered the surface of the Earth. As the Earth cooled, the magma ocean crystallised to form a widespread crust [1]. Another possible explanation was that the melted upper mantle rose up the surface to form a crust. The terrestrial model is the most likely explanation, as the magma ocean could explain some properties of the Earth's crust. The uniform composition of the crust could be formed by a homogeneous magma ocean. The layered composition of Earth's crust may be due to the cooling of magma oceans over time. Thus, the terrestrial model most likely explains the formation of the Earth's crust.

2.2 Origin of the oceanic crust

The oceanic crust was formed about 4.5 billion years ago, earlier than the first appearance of the continental crust, and it was first generated along the ocean ridges. The early oceanic crust differs from the present oceanic crust, in terms of its formation speed and thickness. The early crust was likely to be 20 km thick due to the high temperatures of the upper mantle. The higher mantle temperature caused a greater amount of melting in the upper mantle, resulting in more magma released to the surface to form thicker crusts [3]. The formation speed of the early oceanic crust was also likely to be faster than current speeds, due to the higher recycling rates caused by higher upper mantle temperatures [1]. The early oceanic crust is likely to be basalts in composition, and this could have resulted in the first plate tectonic activity. The basalt crust is denser than the molten mantle, so the basalt crust could have subsided into the upper mantle, leading to the recycling of crusts [3].

2.3 Origin of the continental crust

The oldest continental crust appeared about 4 billion years ago; however, granite continental crust only appeared about 3 billion years ago. There is no other planet in the solar system that has a continental crust except our Earth, mainly because it requires the presence of water on a planet and the subduction of crusts [4]. The seawater cools the hot mantle at the subduction zones, and it allows fractional crystallisation to take place to produce a granite crust [1].

3. Structure

The Earth has a thin silicate crust, which makes up 1% of the Earth's volume [5]. It is the uppermost top component of the lithosphere and floats on top of the upper mantle [6]. The crust plus the upper mantle is separated by the Mohorovicic discontinuity—a seismic and compositional boundary [6]. The crust varies in thickness as controlled by the law of isostasy according to Airy's model—the crust responds to topographical changes (loads or unloads) by changing its thickness as compensation, thus tending towards isostatic equilibrium [7]. The crust is thickest under mountain ranges and thinnest under mid-ocean ridges [6].

There are two main types of crust, the continental crust (underlie continents) and the oceanic crust (underlie ocean basins), the latter being denser and thinner but both being less dense than the mantle [6]. Approximately 35% of the Earth's crust is continental, while the other 65% is oceanic [8]. Continents are generally antipodic to oceans [9]. Conrad discontinuity, which lies at a depth of 5–20 km, separates the continental crust and oceanic crust [1]. Unlike continental crust, the oceanic crust has no granitic zone, but the mantle beneath the oceanic crust is possibly richer in radioactive elements than the mantle below the continental crust. The different locations of heat sources and thermal conductivity of the crust give rise to temperature variations in the different crust types.

Within the continental crust, there are four layers—the upper, middle, lower and the lowest layers [10]. The first layer is mainly made of sedimentary rocks and volcanic rocks, and the P-wave velocities in this layer are less than 5.7 km/s [10]. The second layer is mainly made of granitic plutons and metamorphic rocks (low-grade), and the P-wave velocities in this layer are between 5.7 and 6.4 km/s [11]. The third layer is mainly made of gabbroic cumulate, and the P-wave velocities in this layer range from 6.4 to 7.1 km/s [10]. The fourth layer is usually thin or missing [11], and the P-wave velocities in this layer are between 7.1 and 7.6 km/s [10].

The crust is carried as plates, which are slabs of lithosphere that carry oceanic crust, continental crust or both. They are carried by convection currents in the mantle, a process known as plate tectonics, which is driven by internal heat [1]. The plates meet at plate boundaries, which can be convergent boundaries, divergent boundaries or transform faults [1]. Interactions at plate boundaries, such as between crusts or between the crust and the mantle, can give rise to tectonic features such as oceanic ridges and volcanic arcs [6]. The crust undergoes physical and/or chemical changes in response to these interactions. For example, new oceanic crust develops at the opening rifts of divergent boundaries, forming mid-oceanic ridges through ridge push [12]. At convergent boundaries, dense oceanic crust subducts (slab pull) and produces magma due to the partial melting caused by the mantle's heat (thus creating a hotspot under the crust), which may rise and erupt, resulting in the formation of volcanic features, such as volcanoes, volcanic arcs and islands, on the non-subducted converging oceanic or continental crust [12]. This is seen in the Aleutian Islands. The colliding continental crust would result in the crust deforming into fold mountains [12], and an example of this is the Himalayan mountain range.

Continental margins are long narrow belts [13] that form at the outer edges of major landmasses [14] that include continental and submarine mountain chains. These margins could be passive, active or transform. Passive margins are found between continental and oceanic crust and are tectonically inactive, thus having a smooth relief [14]. Active margins have more tectonic and seismic activity and have features such as volcanoes and high sediment availability [14].

Another notable component of the Earth's structure is ophiolites. These are the fragments of oceanic crust and of the upper mantle that have undergone tectonic emplacement onto the continental crust [15]. They can be incorporated into both passive and active margins [16] and could be evidence of features of ancient oceanic crust that have since been consumed by subduction [15].

4. Composition

Minerals and rocks that make up the Earth's crust are the results of geological activity, density and tectonic plate movement. Minerals have definite chemical composition, whereas rocks are made up of minerals and have no specific chemical composition.

The three main kinds of rocks: igneous, sedimentary and metamorphic. Igneous rocks are formed by crystallisation of magma or lava. Sedimentary rocks are formed from lithification. Metamorphic rocks are formed from igneous and sedimentary rocks that undergone high temperatures and pressures, stress and fluid activity. The rock cycle ensures that these rocks are constantly replenished and recycled on the Earth's crust. Amongst the rocks, igneous rocks and metamorphic rocks make up 95% of the rocks [17], with granite and basalt having the largest compositions amongst the igneous rocks.

There are more than 3000 known minerals. Amongst them, only about 20 are common, and eight of these constitute 99% of the minerals in the crust. They are all silicates and are also called rock-forming minerals. Amongst the silicates, feldspars are the most abundant with plagioclase being the largest portion [18]. Minerals are formed by crystallisation through cooling of magma or lava and liquids. Another process is the evaporation of the liquid containing minerals, which result in the precipitation of material in the form of mineral veins.

4.1 Chemical composition

Elements are the building blocks of minerals. Oxygen and silicon are the most common elements in the crust (**Figure 1**). The Earth's crust consists of both oceanic crust and continental crust. Despite silicates being the most abundant minerals in both crusts, there are still some differences in their characteristics (**Table 1**). Thus, deriving the average compositions of each respective type of crust is essential and critical to investigate the continents and the Earth as such knowledge provides insights into the origin and characteristics of the crusts.

There are three primary methods used to study the Earth's composition: (1) studying and interpreting the seismic profile of both the core and mantle, (2) studying other planets and meteorites and comparing and inferring their composition and (3) using the pyrolite model [19]. Data from all complementary fields need to be integrated to allow a comprehensive and consistent understanding of the current dynamic structure and composition of the Earth.

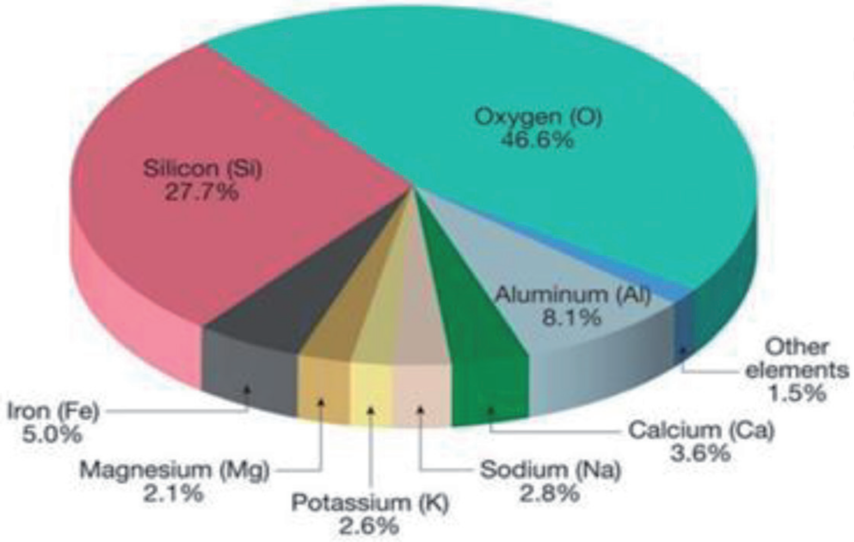
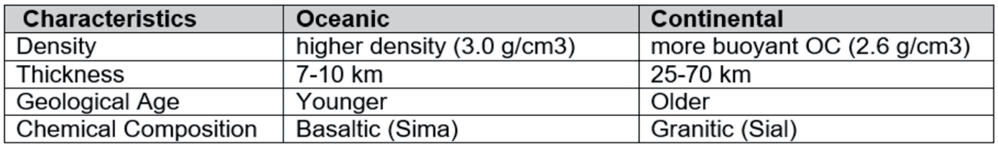


Figure 1.
Composition of elements of the Earth's crust.



Characteristics	Oceanic	Continental
Density	higher density (3.0 g/cm3)	more buoyant OC (2.6 g/cm3)
Thickness	7-10 km	25-70 km
Geological Age	Younger	Older
Chemical Composition	Basaltic (Sima)	Granitic (Sial)

Table 1.
Difference in characteristics.

4.2 Continental crust

Based on seismic investigations, the structure of continental crust is defined to consist of the upper crust, middle crust and lower crustal layers [10, 20]. Each layer varies slightly in its composition. The bulk composition is made mostly of rocks with a composition similar to granite rocks, full of substances such as oxygen, aluminium and silicon.

4.3 Oceanic crust

Similarly, oceanic crust is also layered, and each layer varies slightly in its composition [21]. In general, oceanic crust is basaltic and is rich in minerals and substances like silicon, oxygen and magnesium. To determine the chemical composition, it is important to look into mid-ocean ridge basalt (MORB). All the MORB reflects the mean composition of no or the zero-age ocean crust apart from back-arc basins [22].

5. Evolution

The evolution of the crust would refer to the gradual development of the crust over time. Geomorphically significant evolution of the Earth's crust falls into two main categories, endogenic processes from forces that originate within the Earth and exogenic processes that are a result of forces from above or on the planet surface.

5.1 Endogenous factors

Continental crust transforms into oceanic crust in a cyclic and dynamic process [23]. Where the old crust is being destroyed at convergent boundaries, new crust is being created at divergent boundaries. When rifting first occurs at divergent boundaries, the crust-mantle system transforms due to the temperature, and a rift forms. Subduction of the low-velocity zone in the upper part of the crust is the main mechanism overlooking the beginning of crustal attenuation. Intruding magma, originating from the mantle under the rift, modifies the intermediate and lower crustal layers. As the process continues, a "pseudo-oceanic" crust forms, which has an intermediate chemical composition. Before the new oceanic crust is created, the intermediate crust disappears completely, and the underneath crustal layer is critically modified by bouts of magma from the mantle sources. New oceanic crust is then produced from the ridge and spreads out from the spreading centre towards the subduction zone where the crust is eventually destroyed. Components of the crust will return to the upper crust in different forms such as igneous intrusions and contribute to the formation of new continental crust [21].Depending on the type of plate boundary and the types of plates involved, the resultant processes and landforms formed differ. The different phenomena that occur contribute to the evolution of the crust.

Another example of the evolution of the crust due to endogenous processes is volcanism, where material from the mantle or the deep crust is deposited onto the surface where it contributes in renewing the crust surface with new igneous rock and landforms. In some places the crust is weaker such as along plate boundaries, the magma forces its way through the rock, extruding rock and releasing pressure, which is why volcanic activity tends to occur near the borders of tectonic plates, for example, the Pacific Ring of Fire [22]. The composition and origin of the lava determine the type of volcanic landform created, with more fluid mafic lava forming structures such as shield volcanoes and more viscous felsic lava forming structures such as stratovolcanoes from the accumulation of ejecta. However, in cases where magma does not breach the surface, the magma in horns or magma chambers may solidify to form intrusive or plutonic rocks. Over time, the surrounding softer rock erodes away, revealing the harder plutonic rock beneath, which creates landforms such as plutons, batholiths, dykes, sills, laccoliths and volcanic necks.

5.2 Exogenous factors

The evolutionary processes mentioned above were all a result of forces originating from within the Earth. However, the crust is also shaped by a multitude of processes from external forces such as climate and extraterrestrial material. An overt example of an extraterrestrial force on the crust would be an impact crater, in which materials from space such as asteroids, meteoroids or comets collide with the Earth, leaving scars on the surface. While fairly infrequent in recent geological time, impacts were a major force of change during the late heavy bombardment period of the Earth's history [24], as the orbital path of the planet had not been fully cleared. The size of the impactor and extension diameter of the resultant impact crater is a decisive factor on the type of crater formed, with crater diameters above 2 km for sedimentary rocks and 4 km for crystalline rocks having a more complex impact structure as opposed to a simple bowl shape [25].

Climate and weathering are also significant drivers in the continued evolution of the crust. And while the parameters that control climate are complex and not fully understood, its effects can be seen widely. These processes can be observed in many forms, such as the exposure of batholiths by the erosion of soft rock, the carving of the Grand Canyon or the deposition of sediment by fluvial processes to create river deltas [26].

Additionally, biological processes also play a role in weathering and erosion. For example, plant roots hold the soil together, providing resistance to erosion [25]. Plants and burrowing animals also contribute to the mechanical breakdown of rock through wedging caused by growth and burrowing, respectively. All of the above processes are but a fraction of the factors that keep the Earth's crust in a state of constant flux. And while we may be unable to observe all geological evolutionary phenomena in the span of a human lifetime, we have more than enough examples and evidence to show that truly drastic changes occur in geological time.

6. Summary and conclusion

While the crust may only comprise the superficial layer of the Earth, it is truly a dynamic and fascinating thing to learn about. Superficially appearing to be a solid immutable covering of rock on our world, it is actually a collection of gargantuan rock plates of heterogeneous composition floating upon an equally colossal ocean of magma that is the outer mantle. From its early origins as a hot lifeless shell covering our planet to its current state as the home for all life on Earth, it has changed so much over the geological timespan of the Earth's history and continues to evolve to this day. It is fortunate that the Earth would coincidentally have the perfect chemical composition to form a crust suitable for life forms to exist, all in accordance with the physical laws that govern the formation of worlds. The crust is truly an amazing and astonishing thing to learn and behold.

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